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14. ABSTRACT

In ocean wave-field evolution, nonlinear effects affect the propagation velocity of each wave component in the wave field, produce locked wave components, cause modulational instability development, and enable resonant wave-wave interactions. All of these influence the spatial and temporal variations of the sea surface shape. The nonlinear effects are dependent on wave spectrum parameters (such as wave steepness, bandwidth, and propagating direction) and propagation distance and evolution duration of the wave-field. The main objective of this project is to develop understanding and characterization of nonlinear effects in phase-resolved ocean surface wave-field evolution.

15. SUBJECT TERMS

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Understanding and Prediction of Nonlinear Effects in Wave Propagation

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LONG-TERM GOAL

To understand and quantify nonlinear effects in ocean wave propagation and to obtain reliable prediction of extreme wave statistics and events by applying large-scale phase-resolved nonlinear wave-field simulations. For wave propagation, to develop specific guidelines to conditions under which linearized, higher-order approximate and fully nonlinear propagation models are adequate and required. For extreme wave statistics, to obtain extensive datasets of nonlinear exceeding wave height and/or wave crest height probability functions for wide ranges of nonlinear spectrum parameters, which will enable the development of look-up table for the efficient prediction of occurrence of extreme events in practical applications.

OBJECTIVES

Nonlinear effects affect the propagation velocity of each wave component in the wave field, produce locked wave components, cause modulational instability development, and enable resonant wave-wave interactions. All of these influence the spatial and temporal variations of the sea surface shape. The nonlinear effects are dependent on wave spectrum parameters (such as wave steepness, bandwidth, and propagating direction) and propagation distance and evolution duration of the wave-field.

The main objective of this project is to develop understanding and characterization of nonlinear effects in phase-resolved ocean surface wave-field evolution. In order to reach this objective,

- We perform a large number of simulations of direct phase-resolved nonlinear wave-field evolution for 2D and 3D wave-fields with broad ranges of wave parameters.

- Based on these simulated nonlinear wave-fields, we characterize the dependence of nonlinear effects and provide guidance on modeling/forecasting of phase-resolved wave propagation in different sea states.

APPROACH

Nonlinear effects can be of importance in ocean surface wave-field evolution depending on sea state conditions as well as evolution duration and distance. Understanding and proper modeling of the nonlinear effects is critical for phase-resolved prediction of the dynamics of the wave field. We aim to quantify the dependence of the nonlinear effects in phase-resolved wave-field evolution upon wave-field parameters and propagation distance/duration. This research is relevant and useful to the ONR ESMF program in the development of the real-time capability for a short-time (~30s) forecasting of phase-resolved wave-field evolution based on area and/or point sensed wave data.

To tackle this problem, we apply direct phase-resolved simulations of nonlinear wave-field evolution. The computational tool used is the so-called SNOW (**s**imulation of **n**onlinear **o**cean **w**aves) which has been developed and continuously improved over the past twenty years at MIT under the support of ONR. In SNOW, key physical mechanisms such as nonlinear broad-band wave-wave interactions and wave-breaking dissipation are modeled and calibrated in a direct physics-based context. Unlike statistics-based (i.e. phase-averaged) approaches, SNOW obtains deterministic predictions wherein precise ocean surface and particle velocities are given. SNOW is developed based on a high-order pseudo-spectral method, which follows the evolution of a large number (N) of wave modes and accounts for their nonlinear interactions up to an arbitrary order (M). Significantly, SNOW obtains an exponential convergence and requires a (nearly) linear computational effort with N, M. It is an ideal tool for direct simulations of realistic ocean wave-field evolution.

The effectiveness of SNOW in the mechanistic studies of nonlinear wave dynamics including the effects of nonlinear resonant wave-wave interactions, modulational instabilities, nonlinear wave-bottom interactions, and nonlinear wave-current interactions have been well established (see Mei, Stiassnie and Yue 2005). Large-scale SNOW computations have been applied to study nonlinear statistics of realistic ocean wave-fields (see Yue 2008). Moreover, SNOW computations have been successfully used to investigate the occurrence probability and dynamics of rogue wave events (Xia et al 2013). SNOW has also been extended to include the effects of viscous dissipation (Wu, Liu & Yue 2006) and density stratification (Alam, Liu & Yue 2009). In addition, by integrating SNOW with area and/or point wave measurement, a powerful phase-resolved wave reconstruction and forecasting capability has been enabled (see Yue 2008).

For the study of nonlinear wave effects on wave propagation, in this project, routine large-scale SNOW simulations of nonlinear wave-field evolution in a domain of $O(10^{1\sim2})$ km^2 with evolution time up to O(5) minutes are performed. Each such simulation typically uses $N= O(10^{3\sim4})$ wave modes per dimension and nonlinearity order $M = 3\sim4$ including bounded wave effects, nonlinear effects on wave propagation speed, modulational instability, and quartet resonant wave-wave interactions. These simulations are performed on the high-performance computing (HPC) platform at the Vortical Flow Research Laboratory of MIT.

WORK COMPLETED

We focused on SNOW computations of large-scale nonlinear ocean wave-field evolutions for various wave spectrum parameters and on understanding of nonlinear effects in ocean wave-field propagation. Specifically,

1. We performed large-scale SNOW computations of three-dimensional (short-crested) ocean wave-field evolution for six different sea states. The wave spectrum parameters are specified by APS. Both linear and nonlinear evolutions of the wave-fields are obtained. The detailed phase-resolved wave elevations in entire simulated wave-field during the time evolution of the wave-field are obtained and delivered to APS for the purpose of developing effective wave propagation models.
2. We performed additional SNOW simulations of linear and nonlinear wave-field evolutions for broad ranges of wave spectrum parameters in various sea states. The purpose is to create data sets of linear and nonlinear wave-fields for the study of nonlinear effects in wave-field propagation.
3. Based on the datasets obtained in (1) and (2), we investigated and characterized the dependence of nonlinear effects upon wave spectrum parameters, propagation distance, and evolution time. The purpose of this study is to develop guidelines to the conditions under which linearized and nonlinear wave models are adequate and required in ESMF applications.

RESULTS

It is a challenging task to determine the specific conditions under which nonlinear wave modeling must be applied in ESMF applications. In wave propagation, nonlinear effects affect wave propagation speed, produce bounded wave components, cause modulational instability development, and lead to resonant wave-wave interactions. All of these could be of significance in the phase-resolved description of realistic ocean wave-field evolution. These nonlinear effects depend on various physical parameters including wave spectral parameters (such as effective wave steepness, bandwidth and spreading angle), propagation distance, and evolution time. Quantification and characterization of the dependence of the nonlinear effects on these parameters requires a large number of SNOW simulations for the generation of large data sets of linear and nonlinear wave-fields. In this project, we performed a preliminary study to understand how the inclusion of nonlinear effects influences the phase-resolved description of the ocean surface wave-field evolution.

In applications of the ONR ESMF program, an important task in environment prediction is to forecast the short-time (~30s) phase-resolved evolution of the wave-field in the region surrounding a ship with the radius up to several kilometers, based on the wave measurements near the ship. The challenge is to understand the importance of the nonlinear effects in the modeling of wave propagation from the ship. Specifically, it is necessary to know how nonlinear effects in phase-resolved wave-field evolution vary with the wave propagation distance (from the ship near which wave measurements are available) in various sea states. This can be investigated based on SNOW simulations which provide time evolution of the wave fields for given initial wave fields (corresponding to different sea states).

In a wave field, the wave elevation at location x_L is completely determined by the wave components with group velocity in the range (C_{min}, C_{max}), which propagate from the ship location x=0 to the position $x=x_L$. Here C_{min} and C_{max} respectively represent the minimum and maximum group velocities of the wave components in the wave field. To study nonlinear effects in wave propagation from x=0 to x_L is equivalent to investigate the time evolution of the wave field at $x=x_L$ from $t_1= x_L /C_{max}$ to $t_2= x_L$

$/C_{min}$ based on the SNOW simulation. Figure 1 shows a sample comparison of the time variation of the wave elevation at $x_L = 3\lambda_p$ in linear and nonlinear long-crested wave fields. The wave field is specified by a JONSWAP wave spectrum with a significant wave height of H_s = 4m, a peak period of T_p =8s and an enhancement parameter γ=3.0. The time evolution in duration (t_1, t_2) is associated with spatial evolution from x=0 to $x_L = 3\lambda_p$. The difference between the nonlinear wave elevation and linear wave elevation, $\Delta\eta(t)$, is resulted from the nonlinear effects. By integrating $|\Delta\eta|(t)$ over (t_1, t_2), we obtain the mean value and variance of $|\Delta\eta|$ at $x=x_L$ in this specific realization of the wave field. By taking an ensemble average of $|\Delta\eta|$ over a large number of wave-field realizations for a specific sea state, we obtain mean$\{|\Delta\eta|\}$ at $x=x_L$, which represents the nonlinear effects on the wave elevation prediction at $x=x_L$ in this sea state. Figure 2 shows mean$\{|\Delta\eta|\}$ and variance$\{|\Delta\eta|\}$ as a function of x_L for the sea state given by the above JONSWAP wave spectrum. These results are obtained with an ensemble average over 50 realizations. It is clearly shown that nonlinear effects on phase-resolved wave elevation prediction increase as the propagation distance x_L increases.

Based on SNOW simulations of linear and nonlinear wave-field evolution for different sea states, the dependence of mean and variance of $|\Delta\eta|(x_p)$ on wave spectral parameters can be obtained, from which the guidelines on the use of linear or nonlinear wave propagation modeling in phase-resolved wave-field prediction can be developed.

IMPACT/APPLICATIONS

Advances in large-scale nonlinear wave simulations and ocean wave sensing have recently made it possible to obtain phase-resolved high-resolution reconstruction and forecast of nonlinear ocean wave-fields based on direct sensing of the waves. Such a capability can significantly increase the operational envelopes and survivability of naval ships by integration of such capability with ship-motion prediction and control tools.

REFERENCES

1. Alam, M.-R., Liu, Y. & Yue, D.K.P. 2009 Bragg resonance of waves in a two-layer fluid propagating over bottom ripples. Part II. Numerical simulation. *Journal of Fluid Mechanics,* **624**: 225-253.
2. Mei, C.C., Stiassnie, M. & Yue, D.K.P. 2005 Theory and Applications of Ocean Surface Waves, World Scientific, Volume 2.
3. Wu, G. Liu, Y. & Yue, D.K.P. 2006 A note on stabilizing the Benjamin-Feir instability, *Journal of Fluid Mechanics*, **556**: 45-54.
4. Xiao, W.; Liu, Y.; Wu, G. & Yue, D.K.P. 2013 Rogue wave occurrence and dynamics by direct simulations of nonlinear wavefield evolution, *Journal of Fluid Mechanics* [**In press**].
5. Yue, D.K.P. 2008 Nonlinear Wave Environments for Ship Motion Analysis, *27th Symposium on Naval Hydrodynamics*, October 5 – October 10, 2008, Seoul, Korea.

PUBLICATIONS

None

STUDENTS GRADUATED

None

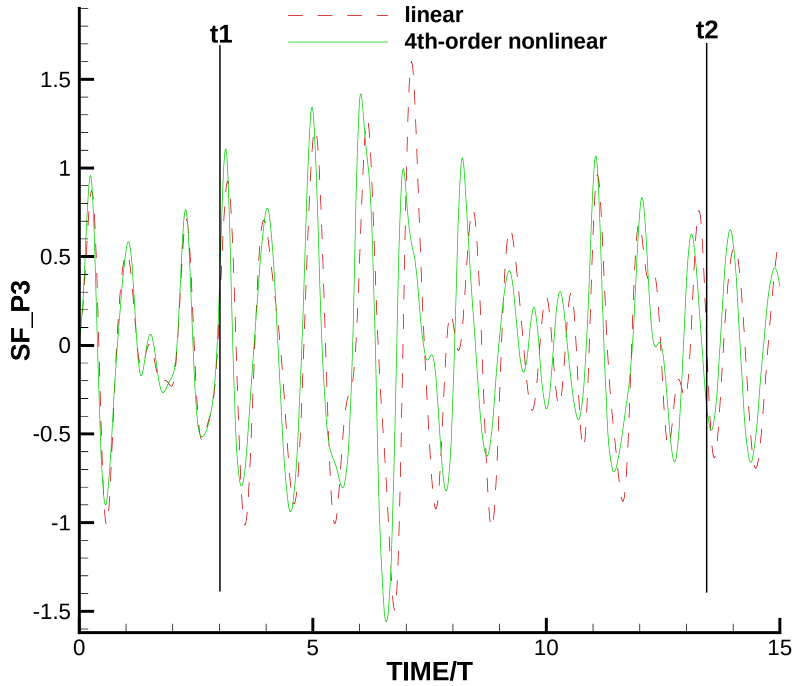

Figure1. Comparison of time variation of the wave elevation at location $x_L = 3\ \lambda_p$ in linear and nonlinear wave fields. The time evolution in duration (t_1, t_2) is associated with spatial evolution from x=0 to $x_L = 3\ \lambda_p$. The wave field is specified by a JONSWAP wave spectrum with H_s = 4m, T_p =8s and γ=3.0.

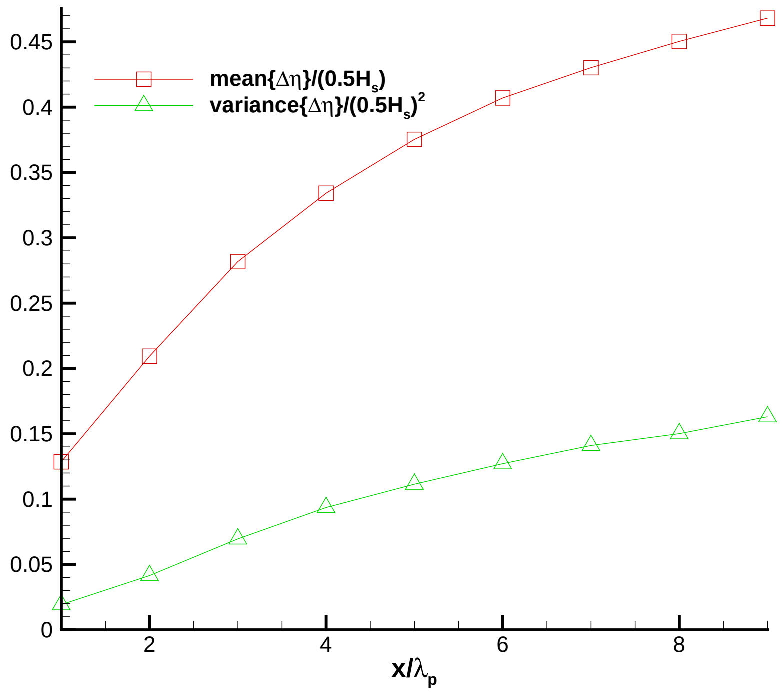

Figure 2. The mean and variance of the difference in wave elevation between nonlinear and linear solution $|\Delta\eta|$ as a function of wave propagation distance. The wave fields are specified by a JONSWAP wave spectrum with H_s = 4m, T_p =8s and γ=3.0.